

# XMM-NEWTON OBSERVATIONS OF X-RAY EMISSION FROM JUPITER

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## ABSTRACT

We present the results of two *XMM-Newton* observations of Jupiter carried out in 2003 for 100 and 250 ks (or 3 and 7 planet rotations) respectively. X-ray images from the EPIC CCD cameras show prominent emission from the auroral regions in the 0.2–2.0 keV band: the spectra are well modelled by a combination of emission lines, including most prominently those of highly ionised oxygen (OVII and OVIII). In addition, and for the first time, *XMM-Newton* reveals the presence in both aurorae of a higher energy component (3–7 keV) which is well described by an electron bremsstrahlung spectrum. This component is found to be variable in flux and spectral shape during the Nov. 2003 observation, which corresponded to an extended period of intense solar activity. Emission from the equatorial regions of the Jupiter's disk is also observed, with a spectrum consistent with that of solar X-rays scattered in the planet's upper atmosphere. Jupiter's X-rays are spectrally resolved with the RGS which clearly separates the prominent OVII contribution of the aurorae from the OVIII, FeXVII and MgXI lines, originating in the low-latitude disk regions of the planet.

Key words: Planets: Jupiter; X-rays.

## 1. INTRODUCTION

Jupiter was first detected as an X-ray source with the *Einstein* observatory (Metzger et al., 1983). By analogy with the Earth's aurorae, the emission was expected to be produced via bremsstrahlung by energetic electrons precipitating from the magnetosphere. However, the observed spectrum is softer (0.2–3 keV) and the observed fluxes larger than predicted from this mechanism. Model calculations by Singhal et al. (1992) confirmed that the ex-

pected bremsstrahlung flux is lower by 1 to 2 orders of magnitude compared with the observed <2 keV X-ray flux. The alternative process is K shell line emission from ions, mostly of oxygen, which charge exchange, are left in an excited state and then decay back to the ground state (see Bhardwaj and Gladstone, 2000, for a review of early work on planetary auroral emissions). The ions were thought to originate in Jupiter's inner magnetosphere, where an abundance of sulphur and oxygen, associated with Io and its plasma torus, is expected (Metzger et al., 1983).

The first *ROSAT* soft X-ray (0.1–2.0 keV) observations produced a spectrum much more consistent with recombination line emission than with bremsstrahlung (Waite et al., 1994; Cravens et al., 1995). Subsequent *ROSAT* observations also revealed low-latitude 'disk' emission from Jupiter (Waite et al., 1997), and this too was attributed to charge exchange. However, the X-rays were brightest at the planet's limb corresponding to the position of the subsolar point relative to the sub-Earth point, suggesting that a solar-driven mechanism may be at work (Gladstone et al., 1998). Scattering of solar X-rays, both elastic (by atmospheric neutrals) and fluorescent (of carbon K-shell X-rays off methane molecules below the Jovian homopause), was put forward as a way to explain the disk emission (Maurellis et al., 2000).

With the advent of the *Chandra* observatory we gained the clearest view yet of Jupiter's X-ray emission, but more questions arose as well: HRC-I observations in Dec. 2000 and Feb. 2003 clearly resolve two bright, high-latitude sources associated with the aurorae, as well as low-latitude emission from the planet's disk (Gladstone et al., 2002; Elsner et al., 2005). However, the Northern X-ray hot spot is found to be magnetically mapped to distances in excess of 30 Jovian radii, rather than to the inner magnetosphere and the Io plasma torus. Since in the outer magnetosphere ion fluxes are insuffi-

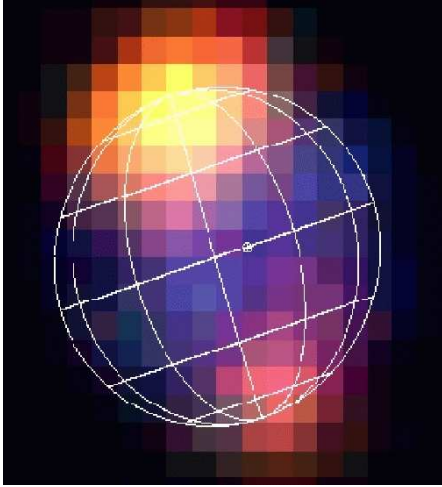


Figure 1. Smoothed XMM-Newton EPIC image of Jupiter (2.9'' pixels), Apr. 2003. North is to the top, and East to the left. Colour code: Red: 0.2–0.5 keV; Green: 0.5–0.7 keV; Blue: 0.7–2.0 keV. The equatorial emission is clearly harder than that from the auroral regions. A graticule showing Jupiter orientation with 30° intervals in latitude and longitude is overlaid. The circular mark indicates the sub-solar point; the sub-Earth point is at the centre of the graticule.

cient to explain the observed X-ray emission, another ion source (solar wind?) and/or acceleration mechanism are required. Strong 45 min quasi-periodic X-ray oscillations were also discovered using *Chandra* data in the North auroral spot in Dec. 2000, without any correlated periodicity being observed in *Cassini* upstream solar wind data, or in *Galileo* and *Cassini* energetic particle and plasma wave measurements (Gladstone et al., 2002). *Chandra* ACIS-S observations (Elsner et al., 2005) show that the auroral X-ray spectrum is made up of oxygen line emission consistent with mostly fully stripped ions. Line emission at lower energies could be from sulphur and/or carbon. The high charge states and the observed fluxes imply that the ions must have undergone acceleration, independently from their origin, magnetospheric or solar wind. Rather than periodic oscillations, chaotic variability of the auroral X-ray emission was observed, with power peaks in the 20–70 min range. A promising mechanism which could explain this change in character of the variability, from organised to chaotic, is pulsed reconnection at the day-side magnetopause, as suggested by Bunce et al. (2004).

## 2. XMM-NEWTON OBSERVATIONS

XMM-Newton observed Jupiter twice in 2003: between Apr. 28, 16:00 and Apr. 29: 22:00 UT (for a total observing time of 110 ks; see Fig. 1, from Branduardi-Raymont et al., 2004, BR1 hereafter), and between Nov. 25, 23:00 and Nov. 29, 12:00 UT (245 ks, split over two spacecraft revolutions, no.s 0726 and 0727; Branduardi-Raymont et al., 2006a,b).

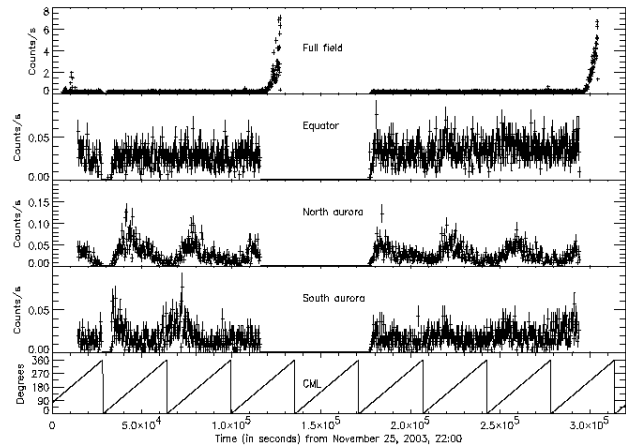


Figure 2. Jupiter lightcurves from the Nov. 2003 XMM-Newton observation. Middle three panels: Low-latitude disk and auroral emissions (0.2–2.0 keV, 300 s bins). Top panel: Lightcurve at energies >10 keV, showing periods of high background (excluded from the analysis) at the end of the two spacecraft orbits. Bottom panel: System III Central Meridian Longitude (CML).

### 2.1. Temporal behaviour

Lightcurves from the Nov. 2003 observation, shown in Fig. 2, resemble very closely those obtained the previous April (BR1). The planet 10 hr rotation period is clearly seen in the data of the North and South auroral spots, but not in the equatorial region. The bottom panel in Fig. 2 shows the System III Central Meridian Longitude (CML). The North spot is brightest around CML = 180°, similar to the Dec. 2000 *Chandra* and the Apr. 2003 XMM-Newton results. A 40% increase in the equatorial flux between the first and the second spacecraft revolution is noticeable in Fig. 2, and is found to be correlated with a similar increase in solar X-ray flux (see Bhardwaj et al., 2005, for a detailed study of the temporal behaviour of the low-latitude disk emission, which appears to be controlled by the Sun). A search for periodic behaviour on short time-scales in the auroral X-rays (i.e. the *Chandra* 45 min oscillations) leads to a null result (as for the Apr. 2003 XMM-Newton data). This supports the view that over time the character of the variability in the auroral X-ray emissions can change from well organised to chaotic.

### 2.2. EPIC spectral images

The XMM-Newton observation of Jupiter in Apr. 2003 gave the first clear indication that the Jovian auroral and disk X-ray emissions have different spectra. Fig. 1 (BR1) is the planet's image colour-coded depending on X-ray energy: the equatorial disk emission is clearly harder than that of the aurorae. The auroral spectra can be modelled with a superposition of emission lines, including most prominently those of highly ionised oxygen (OVII

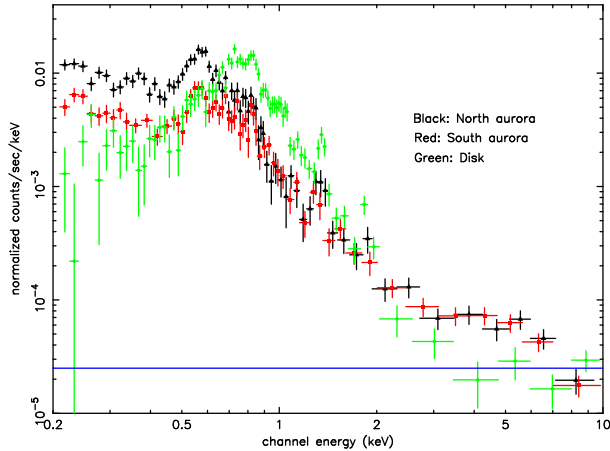


Figure 5. Combined EPIC spectra of the North (black) and South (red) aurorae, and of the low-latitude disk (green) spectrum. Differences in spectral shape between auroral and disk spectra are clear. The presence of a high energy component in the spectra of the aurorae is very evident, with a substantial excess relative to the disk emission extending to 7 keV. The horizontal blue line shows the estimated level of the EPIC particle background.

and OVIII). Instead, Jupiter’s low-latitude X-ray emission displays a spectrum consistent with that of solar X-rays scattered in the planet’s upper atmosphere (BR1). These results are strengthened by the Nov. 2003 observation.

Figs. 3 shows the combined EPIC-pn (Strüder et al., 2001) and -MOS (Turner et al., 2001) CCD images in narrow spectral bands corresponding to the OVII, OVIII, FeXVII and MgXI lines detected in Jupiter’s spectra: OVII emission is concentrated mostly in the North and (more weakly) the South auroral spots, OVIII extends to lower latitudes, while FeXVII and MgXI display a rather uniform distribution over the planet’s disk, consistent with an origin from scattered solar X-rays.

Although most of the X-ray emission of Jupiter is confined to the 0.2–2 keV band, a search at higher energies has produced very interesting results. Fig. 4 (right) is an image of Jupiter in the 3–10 keV band, which shows the presence of higher energy emission from the auroral spots, but not so from the planet’s disk.

### 2.3. EPIC spectra

EPIC CCD spectra of Jupiter’s auroral zones and low-latitude disk emission were extracted using the regions outlined in Fig. 4; the spectral ‘mixing’ (due to the *XMM-Newton* Point Spread Function) was corrected for by subtracting appropriate fractions of disk and auroral emissions from the aurorae and the disk spectra respectively. Fig. 5 compares the resulting spectra of the North and South auroral spots and the disk for the Nov. 2003 observation.

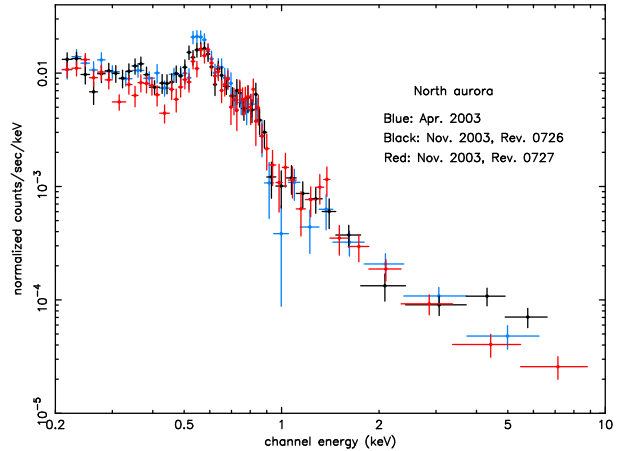


Figure 6. Combined EPIC spectra of the North aurora for the two separate *XMM-Newton* revolutions, 0726 (black) and 0727 (red), in Nov. 2003, and for the Apr. 2003 observation (blue).

As first pointed out by BR1, there are clear differences in the shape of the spectra, with the auroral emission peaking at lower energy (0.5–0.6 keV) than the disk (0.7–0.8 keV). Emission features in the range 1–2 keV are visible in all the spectra, but are stronger in the disk (Branduardi-Raymont et al., 2006b). The presence of a high energy component from the aurorae is confirmed, while this is missing in the disk emission. Variability in the auroral spectra is also observed (Fig. 6): the high energy part of the auroral spectra varies between the two Nov. 2003 *XMM-Newton* revolutions, and changes are also observed at low energies.

### 2.4. EPIC spectral fits

A collisional plasma model (*mekal* in *XSPEC*) with temperature  $kT = 0.46 \pm 0.03$  keV is a good representation of the low-latitude disk spectrum (Fig. 7), after including additional MgXI and SiXIII emission (at 1.35 and 1.86 keV respectively, likely consequences of enhanced solar activity) and a small contribution of OVII (0.57 keV) and OVIII (0.65 keV, both residual auroral contamination).

The auroral spectra are well fitted by a model comprising two thermal bremsstrahlung continua and four gaussian emission lines: these are found at 0.32 keV (C and/or S), 0.57 (OVII), 0.69 (OVII and FeXVII) and 0.83 keV (Fe XVII) for the rev. 0726 spectra; in rev. 0727 and in Apr. 2003 the lowest energy line is not present but one is needed at 1.35 keV (MgXI, probably residual contamination from scattered solar X-rays). The bremsstrahlung continua reflect the presence of two distinct spectral components dominating at the low and high energy end respectively. The temperature of the low energy component is fairly stable, ranging between 0.1 and 0.3 keV and being practically the same for both aurorae. For the higher energy component, the rev. 0726 spectra require a

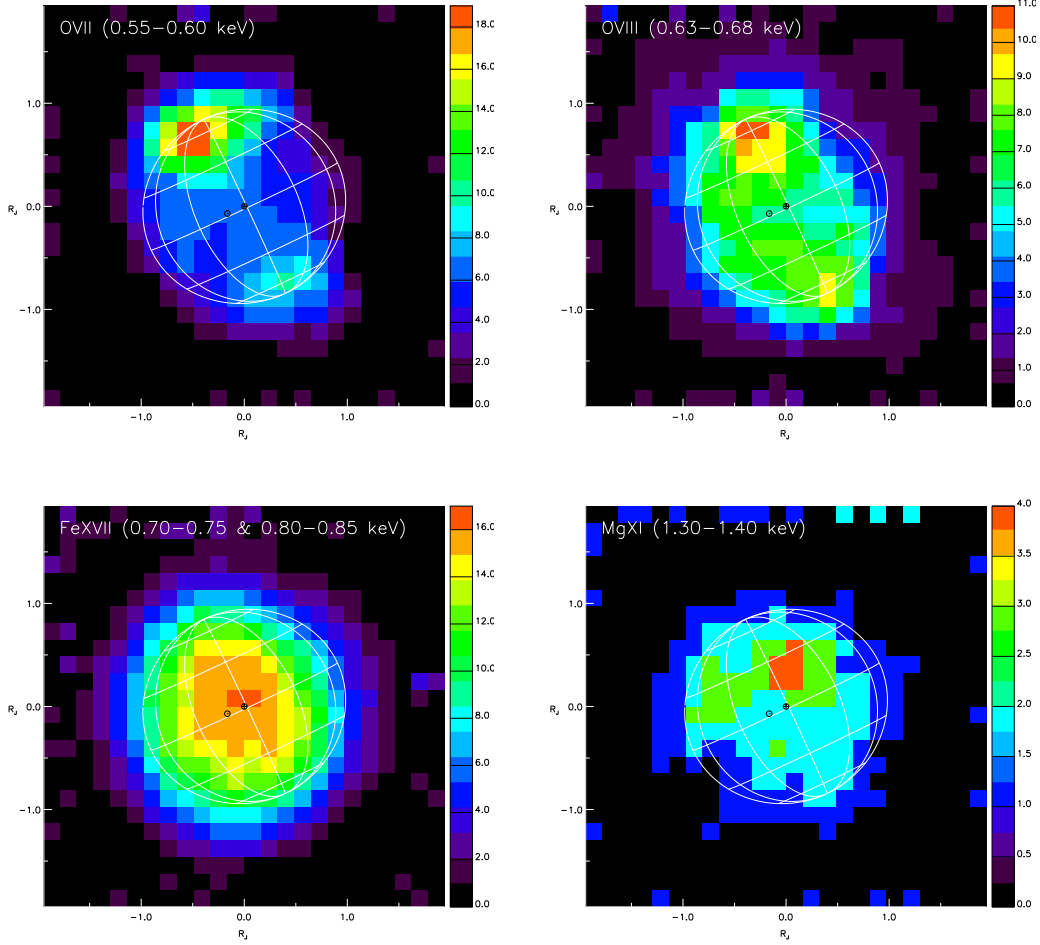


Figure 3. Smoothed XMM-Newton EPIC images of Jupiter in narrow spectral bands. From top left, clockwise: OVII, OVIII, MgXI, FeXVII. The colour scale bar is in units of EPIC counts.

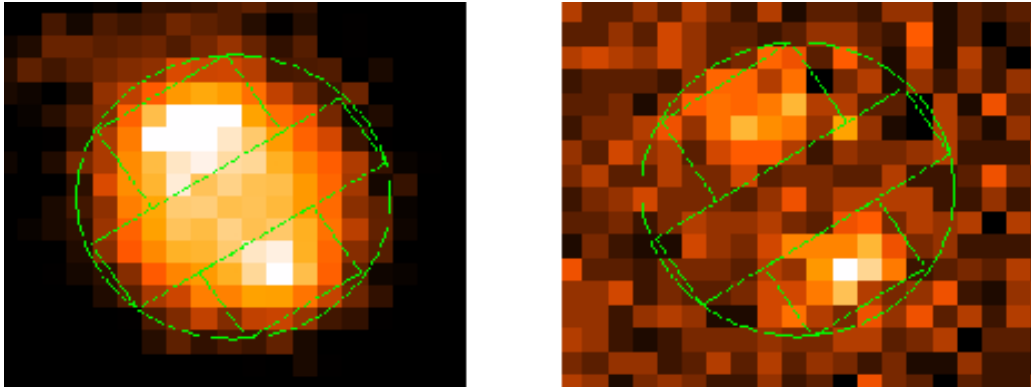


Figure 4. Jupiter's images from the combined XMM-Newton EPIC cameras data ( $\sim 1.4'$  side; left: 0.2–2 keV band; right: 3–10 keV). Superposed are the regions used to extract auroral and low-latitude disk lightcurves and spectra.

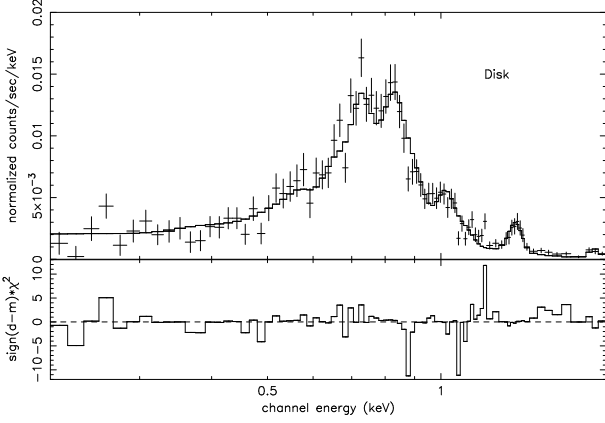


Figure 7. EPIC spectrum of Jupiter's disk and mekal (collisional plasma model) best fit (see text for details).

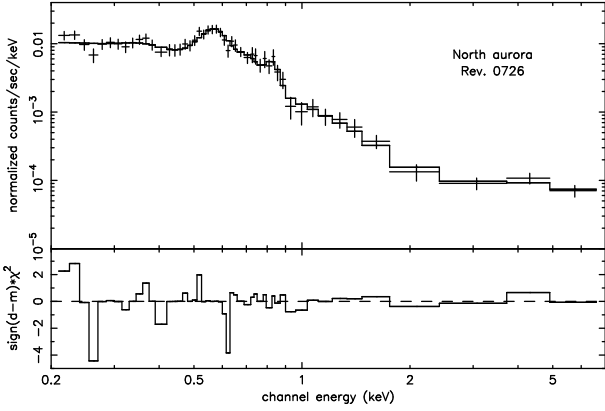


Figure 8. XMM-Newton EPIC spectrum of Jupiter's North aurora from the Nov. 2003, rev. 0726 observation, fitted with thermal bremsstrahlung and power law continua, plus four lines (see text for details).

much higher bremsstrahlung temperature than those from the two other epochs. At the same time the addition of an emission line is needed in order to explain a peak at 0.3–0.4 keV. In actual fact, the spectral shape at the higher energies is better matched by a very flat power law (photon index  $\sim 0.2$ ) than a hot thermal bremsstrahlung. The spectrum and best fit for the North aurora from the Nov. 2003, rev. 0726 observation are shown in Fig. 8.

Fig. 9 displays the high energy continuum model components fitted to the Nov. 2003 auroral data (flat power law for rev. 0726 and steeper bremsstrahlung for rev. 0727) and compares them with the predictions of Singhal et al. (1992) for bremsstrahlung emissions by electrons of energies between 10 and 100 keV. The bremsstrahlung fit of rev. 0727 lies remarkably close to the predicted spectrum for both the North and South aurorae. The models for rev. 0726, however, suggest a very different electron distribution for both aurorae.

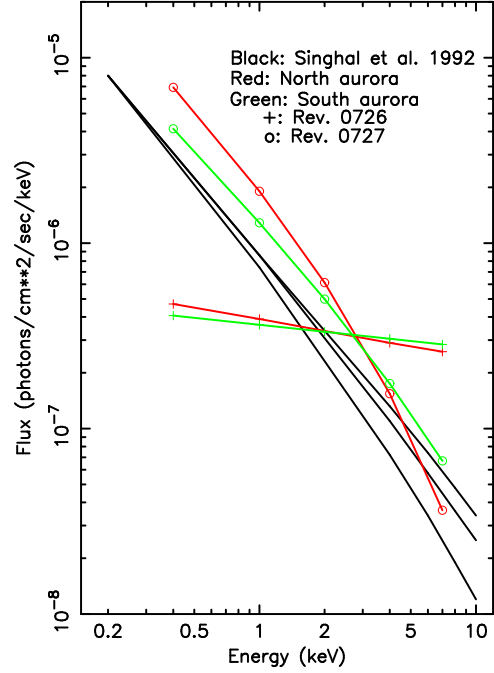


Figure 9. High energy model components fitted to the Nov. 2003 auroral data, compared with Singhal et al. (1992) bremsstrahlung X-ray flux predictions for three characteristic electron energies (10, 30 and 100 keV, from bottom to top curve).

## 2.5. RGS spectrum

Fig. 10 shows the RGS spectrum of Jupiter obtained by coadding the RGS1 and 2 data (first order only) from both XMM-Newton revolutions in Nov. 2003: the image is colour-coded according to the detected flux, and displays the spatial distribution of the emission in the cross dispersion direction versus X-ray wavelength. The RGS clearly separates the emission lines of OVII (21.6–22.1 Å, or 0.56–0.57 keV), OVIII (19.0 Å, or 0.65 keV) and FeXVII (15.0 and  $\sim 17.0$  Å, or  $\sim 0.73$  and 0.83 keV). Interestingly, the RGS spectrum also shows evidence for the different spatial extension of the line emitting regions, in agreement with the EPIC spectral mapping of Fig. 3: OVII photons are well separated into the two aurorae, while the other lines are filling in the low latitude/cross dispersion range. The higher resolution RGS spectrum, which includes X-ray light from the whole planet, agrees well, in flux and profile, with the EPIC one integrated over the full disk of Jupiter (Fig. 11).

## 3. DISCUSSION AND CONCLUSIONS

XMM-Newton observations of Jupiter on two epochs in Apr. and Nov. 2003 convincingly demonstrate that auroral and low-latitude disk X-ray emissions are different in spectral shape and origin. The Jovian auroral soft X-rays ( $< 2$  keV) are most likely due to charge exchange

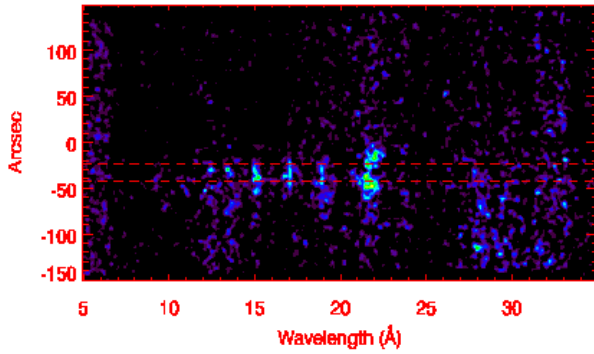


Figure 10. RGS spectrum of Jupiter from the combined RGS1 and 2 datasets of both XMM-Newton revolutions in Nov. 2003; the emission spatial extent in the cross dispersion direction is visible along the vertical axis, while the X-ray wavelength is plotted along the horizontal axis. The two dashed horizontal lines mark the location of Jupiter's aurorae (the planet's N–S axis was essentially perpendicular to the RGS dispersion direction).

by energetic ions from the outer magnetosphere, or solar wind, or both. For the first time a higher energy component in the auroral spectra has been identified, and has been found to be variable over timescales of days: its spectral shape is consistent with that predicted from bremsstrahlung of energetic electrons precipitating from the magnetosphere. The variability observed in its flux and spectrum is likely to be linked to changes in the energy distribution of the electrons producing it and may be related to the particular period of intense solar activity reported in Oct. - Nov. 2003 by a number of spacecraft measurements.

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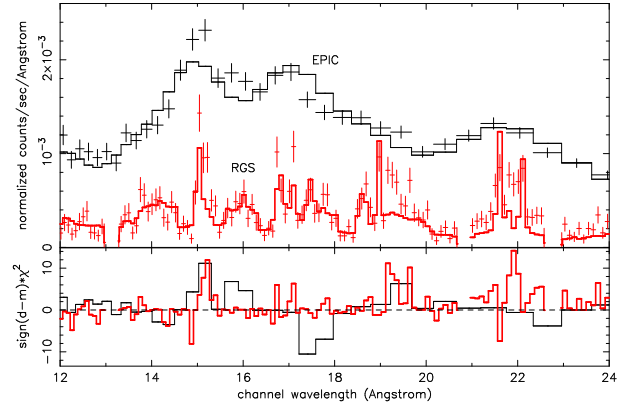


Figure 11. EPIC and RGS spectra of Jupiter (full planet) and simultaneous best fit with a combination of mekal models.

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